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APOLLO 16 GEOCHEMICAL X-RAY FLUORESCENCE EXPERIMENT: PRELIMINARY REPORT

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APOLLO 16 GEOCHEMICAL X-RAY FLUORESCENCE EXPERIMENT: PRELIMINARY REPORT

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ABSTRACT

The lunar surface was mapped with respect to Mg, Al and Si as Al/Si and Mg/Si ratios along the projected ground tracks swept out by the orbiting Apollo 16 spacecraft. The results confirm the observations made during the Apollo 15 flight and provide new data for a number of features not covered before. The data are consistent with the idea that the moon has a widespread differentiated crust (the highlands). The Al/Si and Mg/Si chemical ratios correspond to that for anorthositic gabbro through gabbroic anorthosites or feldspathic basalts. The X-ray results suggest the occurrence of this premare crust or material similar to it as the Descartes landing site.

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APOLLO 16 GEOCHEMICAL X-RAY FLUORESCENCE EXPERIMENT: PRELIMINARY REPORT

INTRODUCTION

An integrated geochemical package was carried in the Command Service Module during the Apollo 16 flight to the Descartes highland area. This package, which was identical to the one carried aboard Apollo 15, included the X-ray, gamma-ray, and alpha particle spectrometers. These experiments were flown to extend our observations to larger areas of the moon and to allow us to extrapolate from the data obtained on the surface to the rest of the moon. Thus, the purpose of the orbital mapping experiment and in particular the X-ray fluorescence experiment on which we are reporting here was to tie together the information obtained from the analysis of the returned lunar samples from the various sites to the global geochemical picture.

There was some overlap of orbital coverage between the two missions so that reproducibility of our results between the two missions could be studied and thus tied together. The total coverage for these two missions is greater than 20 percent of the moon's surface. The Apollo 16 mission provided data for a number of features not previously covered for example Mare Cognitum, Mare Nubium, Ptolemaeus, Descartes area and Mendeleev as well as a number of other areas. One fact of considerable interest was that the X-ray experiment was able to obtain a large number of data points over the Descartes landing site (see Fig. 1 and Table 1) while the astronauts were gathering samples on the surface. Our results will hopefully show how representative these were of the Descartes area.

Unlike the high inclination orbit of Apollo 15, the Apollo 16 flight path was nearly equatorial (9 deg. inclination) so that the projected areas covered were somewhat smaller than during the 15 flight. Although the original flight plan called for a plane change the exigencies of the mission did not permit this; consequently some of the ground coverage was lost.

THEORETICAL BASIS

The theoretical basis for the X-ray fluorescence experiment and a detailed description of the instrument have been described in some detail previously (ref. 1, 2, 3). Briefly the experiment involves the measurement from orbit of the characteristic secondary X-rays produced by the interaction of the solar X-rays with the lunar surface. Because of the spectral nature of the solar flux the measurements were limited to the K spectra of the elements Mg, Al and Si.

The heavier elements are not appreciably excited while the elements lighter than Mg are inefficiently detected. Furthermore the measurements are limited to only that part of the lunar surface illuminated by the sun.

DESCRIPTION OF THE INSTRUMENT

The instrument flown on Apollo 16 was essentially identical to that flown on Apollo 15. It consists of three main sub-systems.

1. Three large area proportional counters with state of the art energy resolution and 0.0025 cm thick beryllium windows

2. A set of large area filters for energy discrimination among the characteristic X-rays of Al, Si and Mg

3. A data handling system for count accumulation, sorting into eight pulse height channels, and finally, for relaying the data to the spacecraft telemetry.

A single multi-cellular baffle type collimator was used to define the field of view (FOV) of the three detectors as a single unit. The FOV was specified as ± 30 deg. full width at half maximum.

An inflight calibration device was used consisting of a rod with radioactive sources of Mg and Mn K radiation. Normally these sources faced away from the detectors, but at regular intervals, an internal signal from the X-ray processor faced these sources towards the detectors. The same X-ray processor was used to condition the X-ray detector outputs for telemetry.

The behavior of the sun's X-ray output was monitored simultaneously with the fluorescence measurements by means of the solar monitor, a small proportional detector mounted on the opposite side of the spacecraft from the surface detectors. On Apollo 16 this detector had an added thin beryllium foil filter in front of the detector window to enable us to look at the high sun X-ray fluxes without experiencing the detector gainshifts observed during the Apollo 15 flight.

OPERATION OF THE INSTRUMENT

The X-ray experiment was turned on initially at 80 hours into the mission and operated for about 12 hours in elliptical orbit (approx. 10 x 16 nautical miles). It was turned on again at 106 hours into the mission with the spacecraft then flying in a circular orbit of about 60 nautical miles above the lunar surface.

As in the Apollo 15 flight, the estimated field of view for each data point used in this report is about 60 x 80 nautical miles. The data were reduced during the mission in the manner described in the Apollo 15 report. Thus it was possible to draw conclusions about the Descartes site and to report these to the crew while they were on the surface.

As indicated above, there was a region of overlap between the Apollo 15 and 16 tracks. This was mainly between 50 and 100 east longitude and covered such areas a Mare Fecunditatis, Mare Smythii, Langrenus, the highlands west of Smythii etc. It is encouraging that for these areas, the Al/Si and Mg/Si chemical ratios for both flights agreed to better than 10 percent (see Table 2). This agreement makes it very encouraging to draw comparisons between the two flights. It also demonstrates that the sun's X-ray spectral distribution, which produces the lunar fluorescent X-rays, was about the same on both missions. This in fact has been confirmed by examination of the Solrad data available for those periods.

RESULTS AND OBSERVATIONS

The following preliminary results and observations are based on the reduction of the data tapes supplied us during the mission. For most part the data points represent 64 second accumulations so that the surface spatial resolution is not optimal. The refined data will be treated at shorter intervals and published subsequently.

The reduced data have been treated in several ways. The Al/Si and Mg/Si intensity ratios have been plotted along the ground tracks and related to gross features as well as other phenomena such as optical albedo.

Figure 1 shows the variation of Al/Si and Mg/Si intensity ratios plotted along the projected Apollo 16 ground tracks. These tracks have been divided into areas based in part on obvious geologic features and in part on intensity contours. Because of the relatively low inclination of the orbit and the repetitive ground tracks there is a high density of data points plotted along the ground tracks. Thus each value shown represents the average of a substantial number of points.

The results in the form of concentation ratios are tabulated in considerable detail in Table 1. A brief summary of our observations follows:

1. Our early reports, given while the mission was in progress, of very high Al/Si ratios in the Descartes area have been confirmed by the analysis of some of the returned lunar samples (ref. 4). The statements made by

members of the preliminary analysis team are that "analysis of the Descartes soils shows a surprisingly high concentration of aluminum oxide compared with samples returned from other sites visited by other Apollo missions". The values reported of 26.5% aluminum oxide agree very well with our own estimates of 26-27%. It appears reasonable, from Fig. 1, that some of the material sampled at Descartes is similar to the eastern limb and farside highlands. This conclusion is further justified by the fact that the Mg/Si concentration ratios for some of the returned materials are about 0.18, close to our values of 0.19 ± 0.05. The eastern limb and farside highlands as shown in Table 1 are about 0.16 - 0.21.

2. The observations resulting from the Apollo 15 flight of high Al and low Mg in the highlands and the reverse of the mare areas is confirmed in the Apollo 16 data. However, there are exceptions; for example, Ptolemaeus had both high Al/Si and Mg/Si.

3. In both missions the Al and Mg values for the most part show an inverse relationship, although this is not true everywhere, as noted in (2) above.

Figures 2 and 3 show a detailed plot of Al/Si and Mg/Si values (intensity and concentration ratios) versus longitude for the projected ground track. Major mare and highland features are identified. Various analyzed materials are shown, for reference, on the right hand concentration scale. Again one observes marked differences between the highlands and the mare areas. The extreme variation in Al/Si is almost a factor of 2 from the low values at Mare Cognitum to the high values in the highlands west of Mendeleev. The Mg/Si ratios generally vary inversely with Al/Si being highest in the maria and lowest the highlands.

One of the results of the Apollo 15 mission was the excellent correspondence between the Al/Si values and the optical albedo values. This observation was particularly significant in view of the long-standing discussion as to whether these albedo differences were solely representative of topographic differences or were also a reflection of compositional differences among surface materials. Early workers such as Whitaker (ref. 5) and others recognized convincing evidence for compositional changes where sharp albedo changes occur, such as between the "red" and "blue" mare contacts, where both units were essentially horizontal. However, it remained for the later Surveyor and Apollo missions to provide qualitative compositional data. Chemical differences related to the albedo were first confirmed by the alpha scattering experiment carried on Surveyors 5, 6, and 7. Surveyors 5 and 6 analyzed widely-separated mare sites and reported chemically similar surface materials for each. Surveyor 7, on the other hand, analyzed a highland site, finding significant chemical differences between it and the two mare locations (ref. 6). The Surveyor results and analyses of returned lunar samples confirmed that albedo is indeed affected by composition as well as topographic differences. The X-ray fluoresence experiment on Apollo 15 and 16 has now provided the means to correlate regional albedo with surface composition (for selected elements).

Data locations for selected Apollo 15 and 16 orbits covered by the X-ray fluoresence experiment were plotted on the photoelectric-photographic map of the normal albedo of the moon done by Pohn, Wildey and Sutton (ref. 7). Average albedo was then computed for each three-degree area for which the X-ray data were available, and plotted against the Al/Si intensity ratios. The positive correlation between the albedo and Al/Si values is strong although the rate of change is not always similar. In the Apollo 15 plots the main anomalies were observed where an occasional small Copernican crater occurred, which produced an abnormally high albedo value. The brightness of these craters is generally considered to be due to the highly-reflective, finely-divided ejecta rather than to compositional changes. A similar anomaly is noted in the Apollo 16 data around 27 degrees east longitude in a Tranquillitatis embayment north of Theophilus. Four Apollo 16 orbits were plotted (see Figure 4) and Orbits 58 and 60 show the expected decrease in Al/Si with decreasing albedo. Orbits 55 and 59, on the other hand, between Orbits 58 and 60, have an <u>increase</u> in Al/Si intensity where the albedo decreases. This may record the existence of old "weathered" ray consisting of aluminum-rich highland-derived ray material which has not lost its high reflectivity.

Several additional anomalies occur, but will not be discussed in this preliminary paper. The chief significance of the albedo-Al/Si correlations is the general similarity of the curves; however, the anomalies required more detailed investigation.

GEOLOGIC INTERPRETATIONS

The results of the X-ray fluorescence experiment from Apollo 16 generally support the conclusions reached after the Apollo 15 mission. However, a more extensive interpretation of the X-ray data is now possible. This interpretation concerns the areal extent of the inferred crustal composition, the nature and origin of the lunar highland crust, and the significance of our findings for theories of the origin of the earth's continental crust.

The most important aspect of the integrated geochemical experiments is that they now give some indication of how representative the returned samples are of the lunar surface in general. The excellent agreement between the Al_2O_3 content of the Apollo 16 soil samples and that inferred from the X-ray measurements demonstrates that these measurements are a reliable guide to at least this aspect of the moon's surface composition. However, the positive correlation between albedo and Al_2O_3 (Figure 4) suggests that if allowance is made for features whose brightness is primarily due to physiographic youth (such as Copernican impact craters), then the albedo is a reasonable guide to highland crustal composition. Apart from its importance in specific areas, such as Descartes, this correlation implies that the plagioclase-rich rocks returned by several Apollo and Luna missions are global in extent, and reasonably though not exclusively representative of the early pre-mare crust.

The good correlation between optical albedo and the Al_2O_3 content suggests an explanation for the unexpected abundance of breccias in the Apollo 16 samples. The Descartes formation, extensively sampled by the astronauts, has been interpreted as volcanic flows and pyroclastics (ref. 8). Head and Goetz (ref. 9) have suggested it to be partially of Copernican age because of its high albedo and spectral, infrared, and radar characteristics. Such a young unit would not be expected to contain such a high proportion of breccia (unless of course they are volcanic breccias). However, the X-ray fluorescence/albedo correlations suggested that the high albedo may be the expression of a high plagioclase content, or a local anorthosite occurrence, rather than a Copernican age. In that case, the Descartes formation could be much older than had been expected, and the abundance of breccias not unusual (even neglecting the possibility of volcanic breccia). Further study will be necessary to see if this explanation can account for the other anomalous porperties of the Descartes region.

It is now fairly well accepted that the moon's pre-mare crust was formed in the first half billion years of the moon's existence, thus representing a period of planetary evolution for which there is virtually no geologic evidence on the earth. Its nature and origin are therefore of great scientific importance (ref. 10). Accordingly, we shall discuss briefly some of the implications of the X-ray data for the evolution of the earth's crust.

First, it will be useful to repeat our initial conclusion from the Apollo 15 data, that the dominant rock type of the lunar highlands appears to be a plagioclase-rich pyroxene-bearing rock, compositionally equivalent to anorthositic gabbro or feldspathic basalt. There are evidently local occurrences of anorthosite, although not so much as to show up on the X-ray data plot (Figure 1). Felsite (such as that in sample 12013) and KREEP also occur, but must be minor constituents of the exposed crust. From the X-ray experiment it is not completely clear just where these occur.

From several lines of evidence, summarized by Lowman (ref. 11), it appears that the first major geologic event in the moon's history was formation of a feldspathic crust, whose remnant now make up lunar highlands. It is important to note that the X-ray and albedo data, coupled with relatively uniform highland crater distribution, indicate strongly that this crust was originally (before excavation of the mare basins) of global extent. However, if a small body like the moon, with relatively little internal energy, could develop a global crust by essentially igneous differentiation, it implies that the earth may have developed a comparably extensive crust early in its history. (This crust would of course have been chemically different from that of the moon in being richer in volatiles and alkalies.) If this in fact happened, crustal evolution since then must have been a process of oceanization rather than of continental growth, inasmuch as the earth's crust is dominantly oceanic. This possibility cannot be explored fully here. However, it appears that the oceanization theory is supported by the existence of a moonwide differentiated crust.

The X-ray fluorescence results may throw some light on the nature of the terrestrial continental crust and the origin of massif anorthosites. The latter have been considered by Hargraves and Buddington (ref. 12) equivalent to the lunar anorthosites, although Romey (ref. 13) finds significant differences. These differences may be due primarily to the deficiency of volatiles (especially alkalies) in the moon and crystallization conditions. It has been proposed by Buddington (ref. 14) and, with modifications, by Anderson and Morin (ref. 15) that the massif anorthosites were formed from magmas that had been generated by partial melting of a primitive plagioclase-rich layer in the earth's crust. As we have discussed, the moon appears to have an originally global plagioclase-rich crust, suggesting by admittedly speculative analogy that the earth may once have had a similar crust. To this extent, the X-ray results imply the existence of a plagioclase-rich layer in the earth's continental crust, from which the parent liquids of the massif anorthosites could have been derived.

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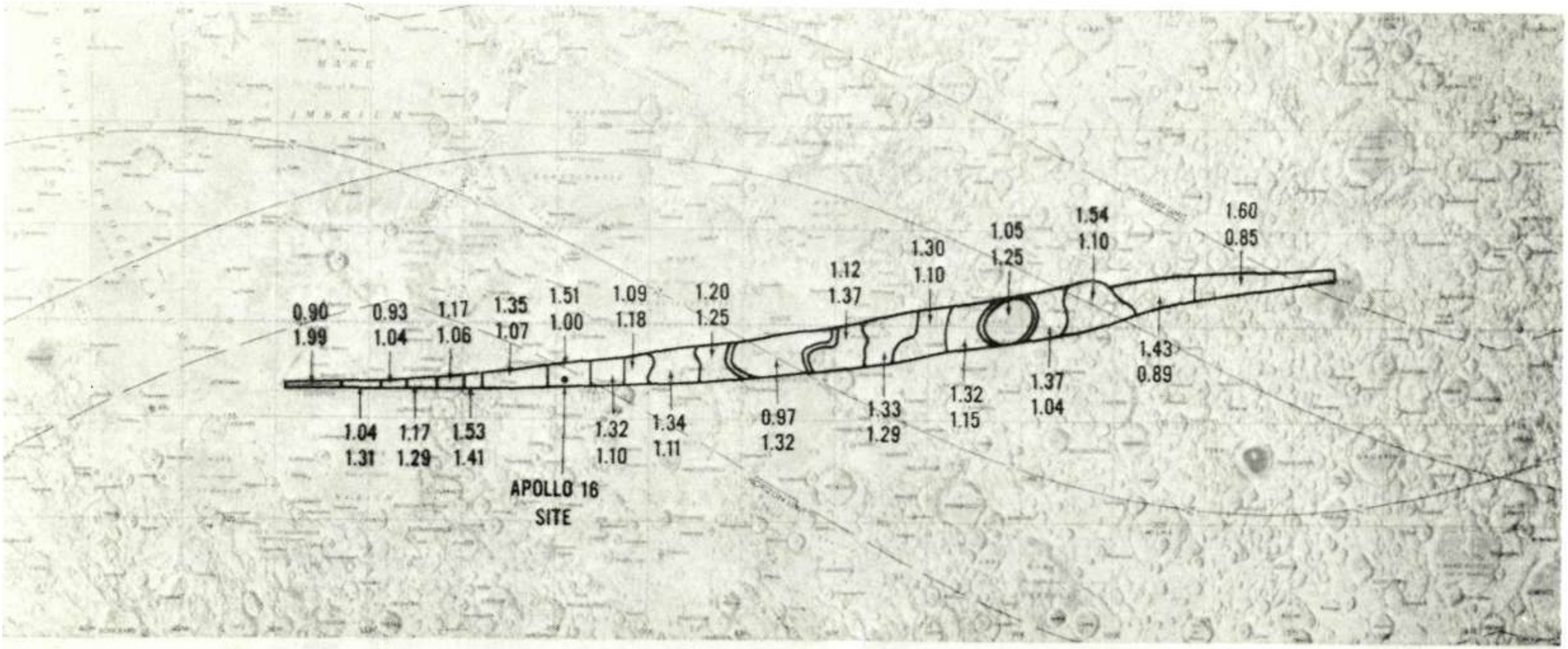

Figure 1. Al/Si and Mg/Si intensity ratios for specific areas along the Apollo 16 ground tracks. The upper values are Al/Si and the lower values Mg/Si.

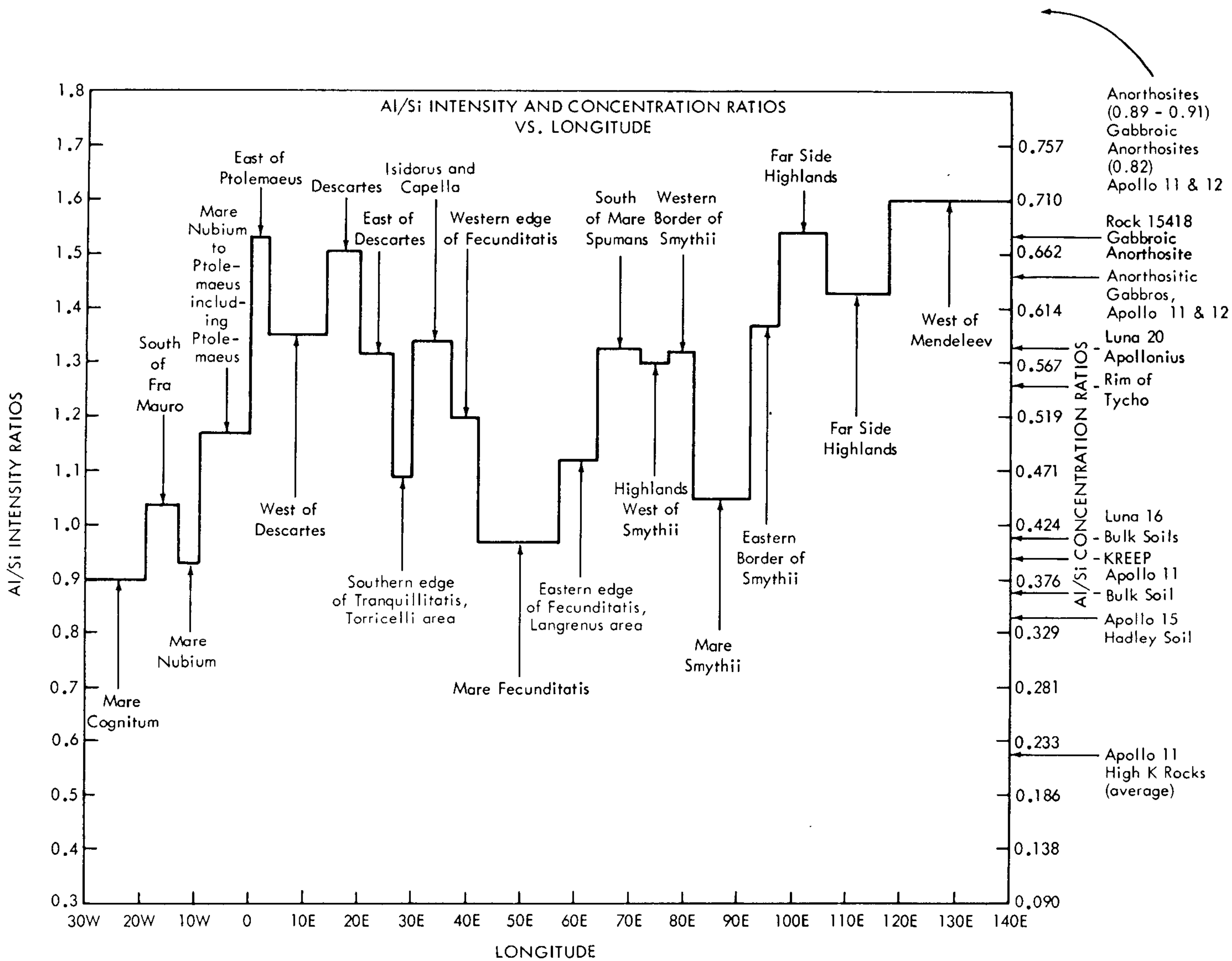

Figure 2. Al/Si intensity and concentration ratios vs. longitude.

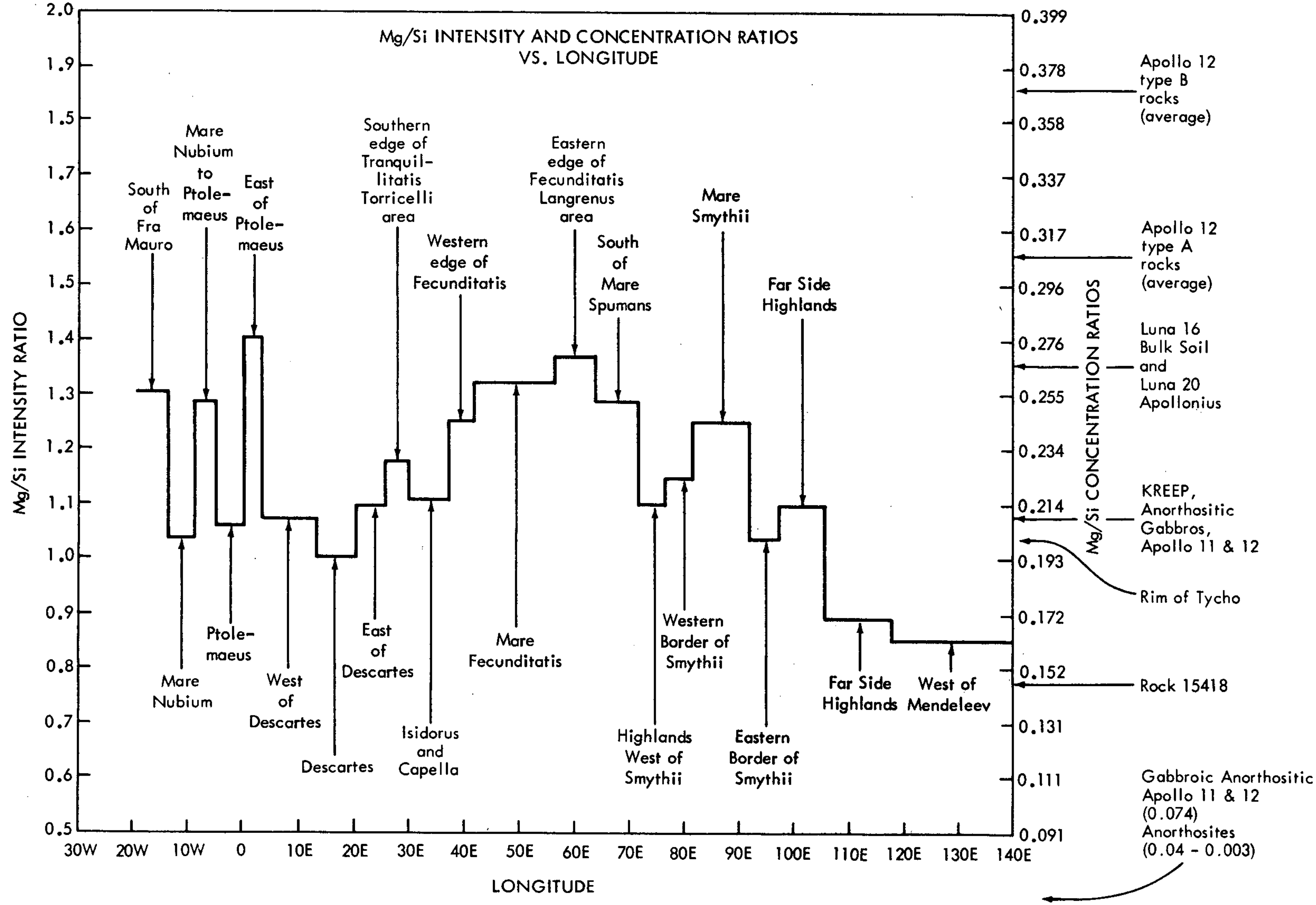

Figure 3. Mg/Si intensity and concentration ratios vs. longitude.

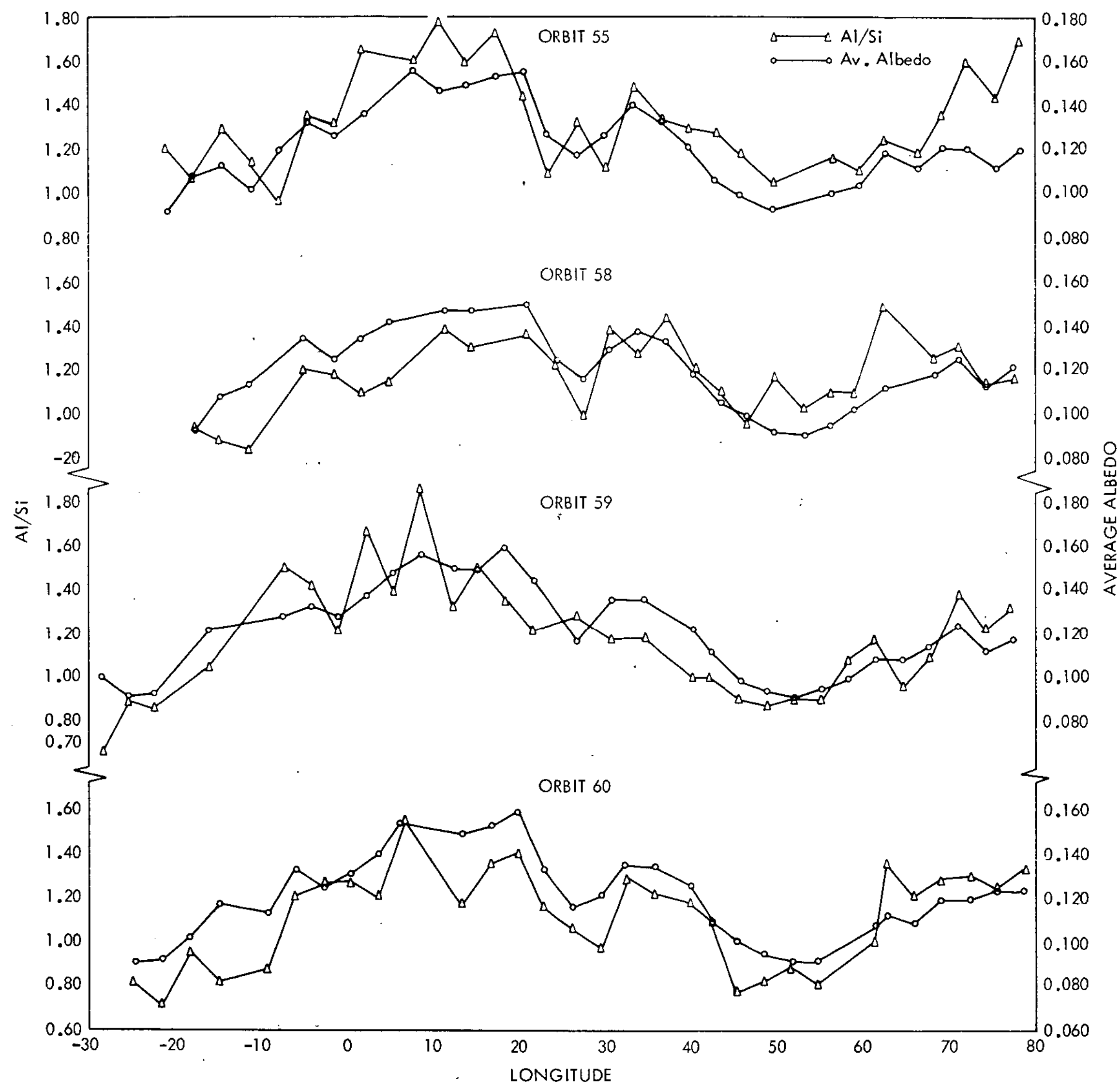

Figure 4. Average optical albedo vs. Al/Si intensity ratios plotted against longitude.

Table 1

Concentration ratios of Al/Si and Mg/Si for the various features overflown during the Apollo 16 remote sensing geochemical mapping experiment.

Feature	N*	Concentration Ratios	
		Al/Si ± 1σ	Mg/Si ± 1σ
Mare Cognitum	8	0.38 ± 0.11	0.40 ± 0.29
Upper Part of Sea of Clouds (9-13W)	8	0.39 ± 0.12	0.20 ± 0.05
Mare Fecunditatis (42-57E)	80	0.41 ± 0.05	0.26 ± 0.05
S. of Fra Mauro (13-19W)	9	0.45 ± 0.07	0.26 ± 0.04
Mare Smythii (82-92.5E)	24	0.45 ± 0.08	0.25 ± 0.05
S. Edge of Mare Tranquillitatis Torricelli Area (26-30E)	21	0.47 ± 0.09	0.23 ± 0.05
E. Edge of Fecunditatis Langrenus (57-64E)	44	0.48 ± 0.07	0.27 ± 0.06
Ptolemaeus (4W-0.5E)	17	0.51 ± 0.07	0.21 ± 0.04
Highlands W. of Ptolemaeus to Mare Nubium (4-9W)	16	0.51 ± 0.11	0.25 ± 0.12
Highlands W. of Mare Fecunditatis (37.5-42E)	29	0.52 ± 0.07	0.24 ± 0.05
Highlands W. of Smythii (72-77E)	35	0.57 ± 0.07	0.21 ± 0.03
W. Border of Smythii (77-82E)	33	0.58 ± 0.08	0.22 ± 0.04
E. of Descartes, Highland (20.5-26E)	23	0.58 ± 0.07	0.21 ± 0.04
S. of Mare Spumans (64-72E)	45	0.58 ± 0.07	0.25 ± 0.04

Table 1 (continued)

Feature	N*	Concentration Ratios	
		Al/Si ± 1σ	Mg/Si ± 1σ
Isidorus & Capella (30.37.5E)	38	0.59 ± 0.11	0.21 ± 0.05
W. of Descartes, Highland (3-14E)	44	0.59 ± 0.11	0.21 ± 0.05
E. Border of Mare Smythii (92.5-97.5E)	17	0.61 ± 0.09	0.20 ± 0.06
Far Side Highlands (106-118E)	29	0.63 ± 0.08	0.16 ± 0.05
Descartes Area, Highland, Apollo 16 Site (14-20.5E)	30	0.67 ± 0.11	0.19 ± 0.05
E. of Ptolemaeus (0.5-3E)	12	0.68 ± 0.14	0.28 ± 0.09
Highlands (97.5-106E)	31	0.68 ± 0.11	0.21 ± 0.05
Farside Highlands, W. of Mendeleev (118-141E)	30	0.71 ± 0.11	0.16 ± 0.04

Al/Si & Mg/Si Concentration of Selected Returned Lunar Samples

Selected Lunar Samples	Al/Si	Mg/Si
Apollo 12, Oceanus Procellarum Average of Type AB Rocks (16)	0.22	0.22
Apollo 15, Hadley Apennines Average of Rocks (17)	0.22	0.27
Apollo 12, Oceanus Procellarum, Type B Rocks, Average (16)	0.22	0.37
Apollo II, Mare Tranquillitatis, High K Rocks - Average (18)	0.23	0.24
Apollo 12, Oceanus Procellarum, Type A Rocks - Average (16)	0.24	0.31

Table 1 (continued)

Selected Lunar Samples	Al/Si	Mg/Si
Rock 12013 (16)	0.24- 0.30	0.20
Apollo II, Mare Tranquillitatis, Average of Low K Rocks (18)	0.29	0.23
Dark of Rock 12013 (19, 20, 21)	0.33	0.22
Apollo 12, Oceanus Procellarum Average of Soils (16)	0.33	0.29
Surveyor VI, Sinus Medii, Regolith (22, 23)	0.34	0.20
Apollo 15, Hadley-Apennines Soils (17)	0.34	0.30
Surveyor V, Mare Tranq. Regolith (23, 24)	0.35	-
Luna 16, Mare Fecunditatis, Rocks (25)	0.35	0.21
Apollo 11, Mare Tranquillitatis, Bulk Soils Average (18)	0.37	0.24
Apollo 14, Fra Mauro, Average of Rocks (26)	0.38	0.26
KREEP Average (19, 20, 21)	0.39	0.21
Apollo 14, Fra Mauro, Soils (26)	0.41	0.26
Norite Material, Average (27, 28)	0.42	0.20
Luna 16, Mare Fecunditatis, Bulk Soils (25)	0.42	0.27
Surveyor VII, Rim of Tycho, Regolith (23, 29)	0.55	0.20
Luna 20, Apollonius Highlands	0.58	0.26
Anorthositic Gabbros, Apollo 11 and 12 (27, 28)	0.64	0.21

Table 1 (continued)

Selected Lunar Samples	Al/Si	Mg/Si
Rock 15418, Apollo 15, Gabbroic Anorthosite (17)	0.67	0.15
Gabbroic Anorthosites, Apollo 11 and 12 (27, 28)	0.82	0.074
Anorthosites, Apollo 11 and 12 (27, 28)	0.89	0.038
Rock 15415, Apollo 15, Anorthosite Genesis Rock (17)	0.91	0.003

*N is the number of individual data points used to determine the average Al/Si and Ma/Si values ±1 standard deviation and was obtained from the various passes over each feature.

Table 2

Reproducibility: Overlap Between Apollo 15 and 16

Feature*	APOLLO 16 (Conc Ratios)		APOLLO 15 (Conc Ratios)	
	Al/Si ± 1σ	Mg/Si ± 1σ	Al/Si ± 1σ	Mg/Si ± 1σ
Mare Fecunditatis	0.41 ± 0.05	0.26 ± 0.05	0.36 ± 0.06	0.25 ± 0.03
Mare Smythii	0.45 ± 0.08	0.25 ± 0.05	0.45 ± 0.06	0.27 ± 0.06
Langrenus Area	0.48 ± 0.07	0.27 ± 0.06	0.48 ± 0.11	0.24 ± 0.06
Highlands West of Smythii (72-77E)	0.57 ± 0.07	0.21 ± 0.03	0.55 ± 0.06	0.22 ± 0.03
West Border of Smythii	0.58 ± 0.08	0.22 ± 0.04	0.52 ± 0.06	0.22 ± 0.06
East Border of Smythii	0.61 ± 0.09	0.20 ± 0.06	0.60 ± 0.10	0.21 ± 0.03

*Note the overlap between corresponding areas of Apollo 16 and 15 are not exact so that differences for the same area stated above may be real (see map).